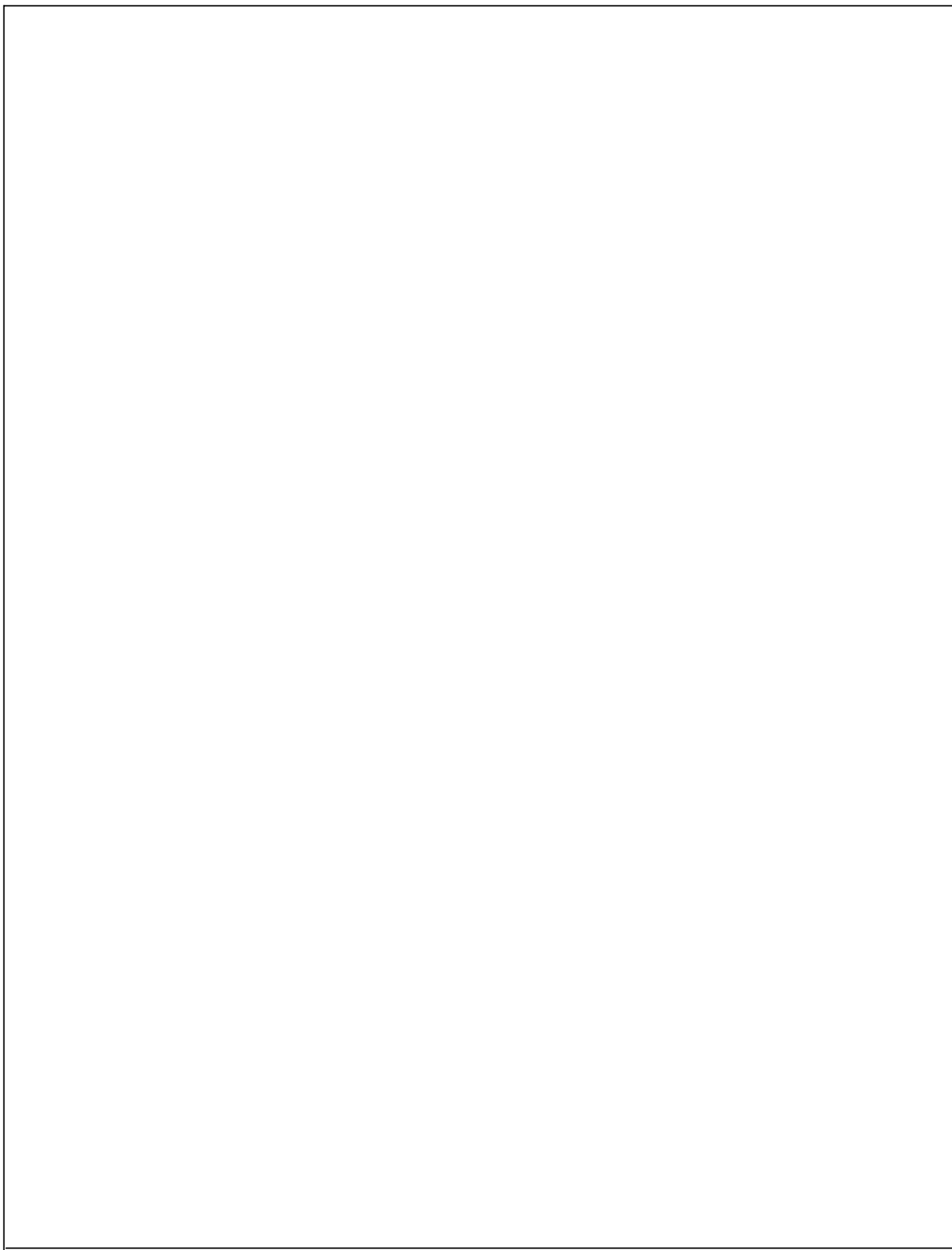


**PROCEDURES FOR THE COLLECTION,
ANALYSIS, AND INTERPRETATION OF
EXPLOSION-PRODUCED DEBRIS—REVISION 1**



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**Department of Defense Explosives Safety Board
Alexandria, VA
22 October 2007**



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14. ABSTRACT In 1999, the first version of a document that attempted to standardize the methodology and procedures used for the collection and analysis of explosion-produced debris information was prepared. It provided a bibliography of available explosion debris information, discussed various methods that might be used to collect and catalog debris information, and concluded by presenting and discussing algorithms that might be used to analyze the data. This original document has proven to be extremely useful and widely disseminated. Debris location techniques have changed dramatically in the last ten years. In addition, it has been shown that some of the original document's recommendations and suggestions need clarification and/or change. Therefore, at the request of the NATO community, the original document has been reviewed and, where appropriate, updated and its contents revised.						
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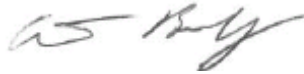
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FOREWORD

Technical Paper (TP) 21 provides Department of Defense Explosives Safety Board (DDESB) guidance and recommendations for the collection and analysis of explosion produced debris. This document represents a revision of the NATO document, NATO AC/258-D/462, first published in 1999. Because this document is derived from a NATO document, the International System of Units (SI) is used throughout.

This document will be kept current and will be updated as new methodologies are developed. The latest version of the document can be found on the DDESB Web-Page:
<http://www.ddesb.pentagon.mil>

This TP has been reviewed by the DDESB Science Panel and the DDESB Staff.



CURTIS M. BOWLING
Chairman
DDESB

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1.0 INTRODUCTION

1.1 Background

In 1997, the original authors were asked by the NATO AC/258 Storage Sub-Group, to "generate a paper on the overall subject of debris collection and analysis" [1]. The result was a paper that was subsequently released as a NATO D/Document [2]. Because of improvements in techniques and methodologies, a revision to this document was deemed not only timely, but also necessary, and in 2006, members of the NATO debris analysis community requested that a review of this document be undertaken in order to update or revise it as necessary [3].

The following hypothetical scenario is proposed. An explosives storage igloo is filled to a high loading density with Hazard Division (HD) 1.1, mass detonating material. An accident occurs, causing the initiation of the structure's contents. As a result, the igloo is completely destroyed and the surrounding structures sustain varying amounts of damage. An examination of the damage shows that it has been caused not only by the blast but also by primary fragments from the explosion and building debris produced by the event. At the extant magazine separation distances, the current regulations consider that the major damage mechanism should be blast (pressure and impulse). However, it is obvious that debris from the igloo and fragmentation from its contents have generated a significant proportion of the observed effects. As a result of the investigation of this accident, it was found that the density of hazardous debris did not fall below an acceptable level within a range of 1200 meters (3937 ft). Current NATO Standards state: "...There is a minor hazard from projections at 400 meters (1312 ft). This is tolerable for ... main public traffic routes ... or all inhabited buildings" [4]. It is apparent from this that the current explosives safety standards are not necessarily adequate and that a greater knowledge of the explosives generation of debris is required.

While not affecting current explosive safety standards, other debris-related processes may affect the results that are obtained. For instance, in some cases with a traversed (barricaded) donor, the hazard from projections may be lower at intermediate ranges. Close in, the debris density may still be high due to traverse (barricade) debris, and in the far field it may increase again due to the high angle debris, which cleared the traverse (barricade).

It is unfair to say that this problem has not been recognized or that work is not being done to address the problem. Internationally, several trials have been carried out to determine the debris generated by explosions inside test structures. On a national basis, analyses have been made of debris data from explosives accidents. From such trials and accident investigations, improvements to both national and international standards have been made and, for some circumstances, models developed to support quantitative risk assessments. A NATO bibliography of references relating to explosion-produced debris contains over 475 entries, dating back over 45 years [5].

This paper discusses the following topics: planning for unplanned events, consistency of approach (in both data recovery and analysis), and credible scenarios. Advice is then provided on the need to consider and define the specific objectives to satisfy the immediate requirement(s), while bearing in mind the broader long-term needs of the safety community. The various methodologies for the collection of debris data are described and the paper concludes by describing the means by which such data could be analyzed in order to meet the desired objectives.

1.2 Objectives

Based on the consequence information obtained after an accident or planned test, quantitative probabilistic risk assessments may be carried out, deterministic safety distances deduced and/or predictive models developed. In all cases, knowledge of the spatial and kinetic energy distributions of the debris is necessary. In an ideal world, a complete, detailed description of the debris field in terms of mass versus velocity versus debris number density is needed as a function of distance from and orientation to the explosion source; however, this is usually not achievable in practice due to time and/or cost constraints. What may be achievable is a measurement of mass versus number of debris versus range or position and an estimate of the distribution of initial velocities. The prediction of velocity-time histories of individual debris pieces is, at best, conjectural due to the indeterminacy of initial velocity, randomness of shape (drag) and the effects of ricochet, roll and bounce. The objective, therefore, must be to achieve the best information practicable, approaching the ideal, to describe the debris field.

The explosives community needs to continually investigate new and improved analysis methods, but still agree on one or more preferred methods, as using different analysis techniques can dramatically change the final outcome of the analysis.

During debris data gathering, be it from an accident or a planned experiment, consistency, definitions and format are very important. The need for consistency in the gathering of the data should also be extended to the analysis. Many of the problems in the analysis of historical explosion effects data lie in the incompatibility or inconsistency of the data collected. In this document, attempts are made to provide a framework for this consistency of approach.

2.0 PLANNING FOR UNPLANNED EVENTS

The dictionary provides the following definition for *accident*: “An unforeseen and unplanned event or circumstance” [6]. An accident in an explosives facility is an unplanned event for which contingency plans must be made. To determine tolerability levels and minimize the risk to personnel and property, an understanding of the potential consequences from the initiation of the explosives within a facility is essential. Currently, there is a reasonable understanding of the effects and consequences of blast in such circumstances but significantly less knowledge exists on the effects of weapon fragments and building debris (hereafter referred to simply as debris).

The consequences of the impact of debris on personnel and property are dependent on the debris mass, velocity, material, shape, number, and impact location. The characteristics of primary fragmentation from the explosion source may be estimated using the methodologies described in References 7 and 8. Corresponding methods for the estimation of secondary fragmentation from structures are not as mature [9-11]. Moreover, these methods do not determine the interaction of that fragmentation with the containing or intervening structure. Debris from the containing structure is generated and projected by the interaction of both the explosion products, i.e., shock and quasi-static gas pressure, and the primary fragmentation with the elements of the structure. Thus, the fragment and debris cloud that is projected into the field around the explosion site is complex and not readily calculable. In practice, therefore, it has been, and will continue to be, necessary to perform testing and modeling in order to quantify these effects. It is also useful to test representative scenarios to gain data for numerical model verification and validation. Additional data can also be gathered from the analysis of accidents. In all cases, a consistent approach for the collection and analysis of such information is needed.

Clearly, in the deduction of tangible data from accidental events, the information to be gained is primarily only that available after the fact. The majority of this information will be descriptors of location (range and bearing), mass, and characteristics. Some secondary evidence may be available to provide estimates of debris velocity, such as the depth of penetration in trees, soil or other materials. However, in the planned experiment, provisions may be made for more extensive, detailed and controlled measurements. An additional and important aspect of the planning process must be the representation of credible and/or worst case accident scenarios.

3.0 PLANNING FOR PLANNED EVENTS (TESTS)

3.1 Pre-Test Preparation

Careful preparation and planning for any test that involves the collection of explosion-produced debris is essential to the successful achievement of its objectives. Every aspect of the test plan and its translation into practice must be considered in the light of the test objectives and their optimal satisfaction. Test objectives should, where possible, include the capture of data that are not directly relevant to the test objectives but that do not add significantly to the cost or resource bill of the test. The data may become invaluable at a later date.

So far as is possible, models should be used to predict maximum debris throw, directionality, velocity and mass distribution(s), as all will play a part in influencing the measurement techniques to be used and the test preparation needed. The software set available for this purpose includes, but is not limited to, DISPRE [10], DISPRE2 [12], TRAJ [13], KG Engineering Tool [14] and various finite difference codes. Software to predict these effects are also included in the consequence prediction algorithms that are embedded in the quantitative risk assessment software under development in various countries. Empirically based models to estimate the effects of bounce, ricochet and roll have been proposed and are under development [15,16]. Although some of these models have been implemented in several countries, they still require validation.

3.2 The Test Range

It is important that the test range should be sufficient in size and condition to meet the needs of the test. Ideally, the area to be used for the test should be flat and clear of obstacles such as structures, trees, other vegetation, widely varying terrain, etc., over a circle (unless a more specific shape such as a quatrefoil pattern can be reliably predicted) centered on the test structure; it should have a radius greater than the predicted maximum debris range. Experience has shown that a safety factor of 20% to 30% should be applied to the predicted maximum debris range when determining the size of the test area. Where range space is limited in some directions, careful orientation of the test structure can be used to reduce the distance required. In some circumstances, little or no wall debris is projected from the corners of the donor structure—the debris scatter pattern being quatrefoil in shape. However, if the structure has a concrete roof and/or strengthened corners, there may be a diagonal contribution from these elements that distorts or eliminates the quatrefoil pattern. The pattern might also be distorted by the presence of traverses (barricades).

In smaller test venues, it may be necessary to limit the directions in which debris effects can be measured. In the directions of interest, it is important that there is sufficient distance to ensure

uninterrupted debris throw—again 120% to 130% of the predicted maximum debris throw is suggested. This might be accomplished by an asymmetric pattern around ground zero. If necessary, the non-measurement directions may be protected by simple, expedient barricades. A sloping topography could also be used to isolate certain factors and conduct sensitivity analyses on the bounce, ricochet and roll phases of the trajectory.

3.2.1 Terrain

While it is difficult to advise absolutely on the flatness of the test area, it is clear that sloping ground will enhance the debris ranges downhill and reduce them uphill. It will also lead to skewing of the debris distributions in the cross-slope directions. In order to minimize these effects, it is recommended that ground slope should be less than 1% over the test area. Again some alleviation may be gained by careful control of test orientation on sites where there are local slope variations.

Inevitably, the test site will be strewn with stones, natural rubble, lumps and hollows. The degree to which these should be cleared, flattened or filled is dependent on the test, the predicted debris characteristics, the availability of financial resources, and the local environmental considerations and regulations. As a rule, only clusters of large boulders that might significantly distort the debris throw (including ricochet, roll and bounce phases) need be moved. In a similar vein, only holes or depressions with the same potential should be filled.

3.2.2 Soil/Geology

It is important that the test site surface is firm enough that debris or fragments landing on it are not lost, i.e., buried in sand or submerged in mud or water. While it is normally impractical to remedy the situation, differences in soil properties should be noted if the variation is not isotropic within the test area. For example, if one direction is significantly sandier (and thus softer), while another side is rockier (and thus harder) than the average soil condition, this information should be recorded. Such differences may well affect test results (debris will more likely, and more dramatically, shatter upon impact with harder surfaces).

3.2.3 Vegetation

There may be a carpet of vegetation over all or part of the test area. This should not be so dense as to impede the scatter of debris or reduce the efficiency of the post-test debris search phase. The degree to which the test area should be cleared will be dependent upon the type of debris recovery techniques to be used. The amount of clearing should be greater if aerial photography is to be used rather than a personnel search on the ground. (NB: Debris recovery techniques are described later in this document.) As before, non-uniformities should be noted if not corrected.

3.2.4 Environmental Coordination

It is the authors' experience that early communication with the environmental and/or conservation authorities responsible for the test area is vital to reduce or avoid conflict where there is a need to clear or modify the topography of the test site. Such conflict, if it is allowed to occur, could delay or jeopardize the trial.

3.2.5 Existing Debris

The test site will, in all probability, have been used for testing previously and will be scattered with old debris. It is essential that there should be no confusion between old debris and that being generated in the planned test. If there is any chance of confusion, the old materials should be cleared. If clearance is not practical, an alternative may be to either mark the old debris with spray paint, color code the source of the debris being produced on the new test, or both.

3.3 The Potential Explosion Site (PES)

3.3.1 PES Design and Construction Specifications

A complete PES description and construction specifications (e.g., material types, dimensions, thicknesses, rebar size and location, etc) must be included in any test report. This information is vital to any modeling effort and may also be necessary in the interpretation of observed results. Location and shape of the charge within the structure is also necessary to allow for accurate modeling.

An inspection of the PES should always be conducted before the test to ascertain the condition of the PES in a quantitative manner.

3.3.2 PES Design Considerations

The PES clearly has to be representative, in terms of building codes and standards, of existing or planned buildings. However, much can be done in the detailed design to improve or extend the debris information gathered. The requirements of risk analysis or safety-distance determination can generally be met with knowledge of the total debris field from the whole structure and its contents. However, when it comes to the development of predictive models, there is a need to identify the source of the individual debris—wall, roof, floor, structure contents, etc.

A choice of bright or unique colors or dyes can also be a simple aid to the efficient location of debris after the event. However, when selecting a color scheme, care must be taken to select colors that do not blend with the surrounding terrain and vegetation. It is the authors' opinion that the incorporation of this type of measure (color-coding of potential debris), which maximizes information retrieval and costs little (in terms of the full test cost), is worth doing even if it goes beyond the immediate aims of the experiment.

For concrete buildings, color-coding of potential debris might be accomplished by adding coloring agents to the various components. Care must be taken, however, to ensure that the addition of these materials does not significantly alter the structural properties of the concrete. It is recommended that pre-test screening be conducted to ensure that the concrete mixes have the desired properties; in addition, test cylinders should be poured at the time of PES construction. These cylinders should then be tested to verify that the concrete has the desired properties both at 28 days (after pouring the concrete) and at test time.

Paint might also be used to color different parts of the structure. In those areas that would be exposed to high temperatures, a paint that is resistant to the effects of such temperatures must be used. A disadvantage to this technique is that the applied color is only skin deep. If the structure is reduced to aggregate-size pieces, as is sometimes the case, the paint may not be helpful.

The design of the PES, and indeed any exposed sites (ES), may have to be in accordance with local building codes and regulations—including requirements for seismic hardening. If this is the case, variances or exceptions may have to be obtained in order to complete the test structure as required at the test site.

3.3.3 PES Ancillary Equipment and Fixtures

Consideration must be given to the choice of ancillary equipment and fixtures to be included in or on the structure. The simple question to ask for each item is: Does its exclusion detract significantly from the debris to be generated or will its absence affect the generation of the debris? If the answer is *no*, then its inclusion in the structure is unnecessary. When addressing this question, there is a need to distinguish between the debris generation and the debris throw mechanisms. For instance, the shock might affect the number of fragments and their mass distribution, whilst the venting could affect the debris throw (NB: the two phenomena are not mutually exclusive).

An example might be a personnel door. While its presence would only contribute a few fragments, its absence might affect the response of the structure. If the door were not present, the opening might represent a vent that could reduce the gas pressures inside the structure. If the net explosive quantity (NEQ) or the loading density (the NEQ divided by the internal volume of

the PES) is such that the direct shockwave is the dominant debris generation mechanism, then the presence of a door will not significantly affect the results. If, on the other hand, the quasi-static gas pressure is a major contributor to the debris generation, then a door should be included. Thus, the inclusion or omission of a door could affect the final debris ranges in the direction of the opening.

A possible exception is the inclusion of lightning protection. A lightning protection system would not affect or add materially to the debris. However, if there is any intention to store explosives in the structure on a temporary basis prior to the test or if the trials authority considers it necessary for the test, then it must be included.

3.4 The Explosives

3.4.1 Selection of Energetic Materials

The type of energetic material selected for the test should reflect the goals of the experiment. Whatever material is selected and used, its output should be well characterized. If it is not, a calibration shot should be conducted under similar conditions (charge shape, height of burst, initiation system, etc.) to the test event. Regardless of the characterization of the explosive donor through the use of one or more calibration tests, time-resolved pressure measurements should be taken during the test to confirm the explosive output for that test.

3.4.2 Transportation and Storage

The explosives must be transported, assembled and stowed in the PES in accordance with the local host nation regulations and the relevant portions of US Department of Defense or NATO Standards [4,17]. When there are differences between the local host regulations and relevant portions of the US Department of Defense or NATO Standards, the more restrictive rules and guidance should apply.

3.4.3 Means of Initiation

The means of initiation of the explosives must be in accord with the aims of the test and meet an acceptable standard. If the test is intended to simulate an accidental fire environment, then a fire meeting the requirements of the UN Test 6c [18] must be arranged. Examples of this are the HD 1.2 tests in igloos carried out in 1993 and 1995 [19,20]. An HD 1.1 test may require multi-point initiation throughout the stack to ensure complete detonation. One method of achieving this is to use multiple detonators/detonating cord distribution lines. For example, on a large stack of MK 82 bombs stored on six-bomb pallets, one bomb per pallet would be primed and initiated. Other

items might require additional priming. (NB: Multi-point initiation, though potentially conservative, ensures that a worst-case scenario in terms of initiation is obtained.)

Cognizance of local range safety regulations must be maintained, as the desired initiation mechanism may be deemed unsafe under certain circumstances.

3.5 Meteorological Limits

Meteorological factors, e.g. rain or wind will have an effect on the test site and may have to be taken into account and test schedules altered as necessary.

Too much or too little rain can both cause problems. It is obvious that periods of excessive rain may cause the test site to become unacceptably muddy or flooded. Other consequences of too much rain may be more difficult to anticipate. Excessive rain may cause local vegetation to flourish and become more dense than usual. Should this vegetation be producing pollen during the planned test, it is possible for the pollen to act like the material in a cloud chamber and produce an opaque layer that could obscure most of the test structures in the videos.

In some places (e.g., Woomera, South Australia) prolonged periods of dry weather can bring their own problems. The dust clouds generated by the expanding blast wave can occlude the fields of view of video or cine cameras, thus reducing their data collection capability. This is difficult to combat. A possible countermeasure is the thorough wetting of the area around the structure with water or petroleum-based products. However, even this may do little to ameliorate matters.

Wind may, of course, exacerbate the dust problem. In addition, wind can also apply bias to the debris distribution, when times of flight are long (seconds) and/or in the case of light debris with large surface areas, where the wind may significantly affect the maximum throw range. As a broad guide, a wind-induced displacement of 0.5 meters (1.7 ft) can be expected for each knot (NB: 1 knot = 0.514 m/s (1.69 ft/s)) of wind and each second of travel. It is recommended that testing should not take place in wind strengths greater than 5.14 m/s (10 knots).

The shot time meteorological conditions (temperature, barometric pressure, wind speed, and wind direction) should be recorded and reported. This information could later be necessary to estimate any meteorological effects on the results obtained.

3.6 Site Survey

3.6.1 Requirements and Accuracy

A survey of the site is required for the following reasons:

1. Determine the location of all cameras, scaling screens/poles and instrumentation
2. Determine the location, orientation, and spatial relationship of all test structures
3. Facilitate debris collection and cataloging

All surveyed grid points should be located to accuracy no worse than 0.1° in azimuth and 0.1% in linear dimension (minimum 0.1 m (0.33 ft)). The accuracy of the grid is not as important and may be somewhat relaxed when locating and cataloging individual debris pieces. (NB: This technique is described in *Section 3.6.3.2 (Location Of Individual Debris Pieces)*).

3.6.2 Camera Locations

To optimize the quality of the data generated from the analysis of video/cine records, it is essential to determine the positions of the cameras and their scaling screens and/or poles relative to a fixed datum.

Except for documentary cameras, where possible, all camera axes should be either in the plane of or perpendicular to the normal of any wall of any structure being observed. Thus, it is essential to locate the position of the structures relative to the fixed datum and define the perpendicular bisectors of each of the walls. Where possible, all cameras should include a known reference point in their field of view. Further camera information is presented in *Section 3.8 (Video/Cine And Related Instrumentation)*.

3.6.3 Planning

The survey requirements for debris collection and cataloging will be highly dependent on the scale of the test and the planned debris data recording method. Recording methods fall into two categories:

1. By location within azimuthally and radially defined zones (*Section 3.6.3.1 (Collection Within Zones)*).
2. By individual debris piece location (identifier, range and azimuth) (*Section 3.6.3.2 (Location Of Individual Debris Pieces)*).

Neither of these techniques inherently addresses the issues associated with modeling post-impact debris behavior. These issues can make it difficult to determine if the test results match the predictions of a model.

The issue is that in many cases, individual fragments will translate (bounce, skid, or roll) after their initial impact with the ground, rather than forming an impact crater. In some cases, this translation may mean that the initial impact point is in one recovery sector but the final position

(i.e., where it came to rest) is in a different one. This leads to the question of where the fragment should be positioned in the recording of the data (*first impact point or final location?*). While different arguments can be made for or against one philosophy or the other, at the very least, it is clear that this is an important decision that should be consistently applied to the data and that should be documented in the test report.

Another issue, which is of particular importance when the donor material is concrete or brick, involves the break-up or shattering of pieces upon impact. If a single large fragment shatters when it first hits the ground, it may scatter hundreds of smaller pieces. Where should these data points be recorded, and as how many pieces? Again, the manner in which this issue is treated must be consistently applied and should be recorded in the test report.

3.6.3.1 Collection Within Zones

If debris is to be collected within pre-defined zones, these areas should be surveyed in prior to the test. Often, these zones will be defined as elements of a radial coordinate system, the origin of which will be at the center point of the PES and the originating axis will be related to the perpendicular bisector of one wall. Radials should be marked at the desired angular intervals, thus defining the width of each sector. The authors have found that a 5° or 10° sector width is suitable in most cases; however, allowance should be made for further sub-division after the event where it is clear that the angular debris density variation is large within the pre-defined interval (NB: This restriction does not apply to those situations where each debris piece is located and cataloged, as will be described in a later section (*Section 3.9 (Post-Event Data Collection)*)).) When using radial zones, care must be taken to ensure that the area of the zone is properly taken into account.

Also of importance is the exact choice of the originating axis position. The first option is to use the normal to the structure wall as a sector divider as shown in Figure 1. The second option, as shown in Figure 2, is to have the normal to the structure wall bisect the sector.

The zonal definition shown in Figure 2 is generally more advantageous and is more often recommended than the one shown in Figure 1. This is because the defined sectors are centered on the normal to the PES walls and would, therefore, be expected to contain the peak density. In the configuration shown in Figure 1, the normal forms the sector boundary; therefore, no single sector can be expected to contain the peak.

Having set the angular width, each sector may be marked at intervals to define the depth of the sector and, thus, the individual search areas. The sector depths will be a function of the scale of the trial and the predicted maximum debris throw distance coupled with the practical limitations of carrying out the debris search. The search area should be marked out to about 1.2 to 1.3 times

the maximum predicted debris throw. Typically, sector depths of about 20 to 30.5 m (65.6 to 100 ft) have been used.

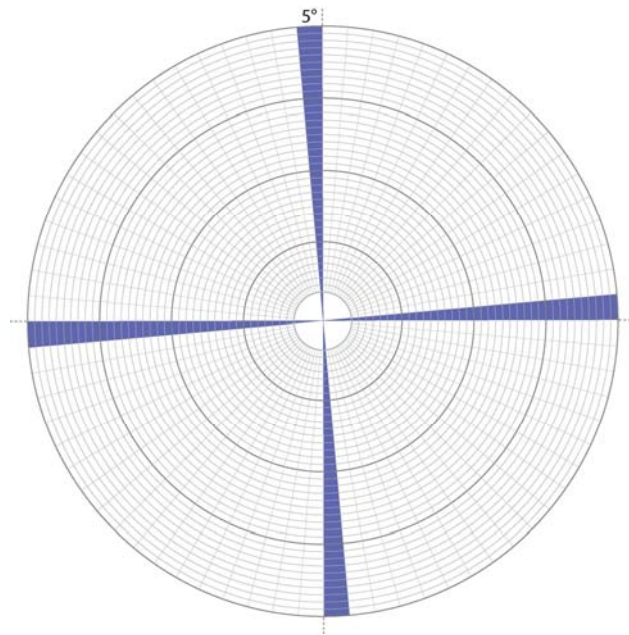


FIGURE 1. COLLECTION WITHIN ZONES: OFFSET SECTORS (EXAMPLE)

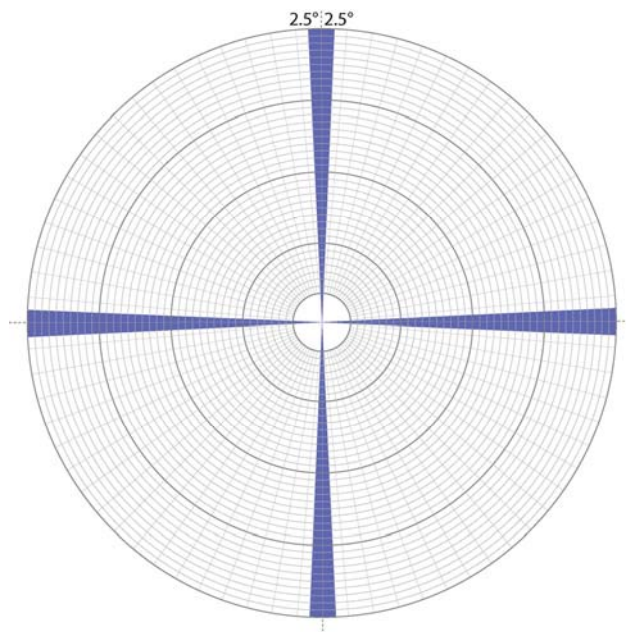


FIGURE 2. COLLECTION WITHIN ZONES: SYMMETRIC SECTORS (EXAMPLE)

3.6.3.2 Location of Individual Debris Pieces

If a post-test survey technique is to be used to locate each individual debris piece, there may be no need to establish sector depths. However, it is strongly recommended that an angular division be surveyed in over the test site to assist in the management of the search operation. The size of the search area will be dependent on the planned search technique. If personnel are to be used to search the area, then the search area will be proportional to the number of personnel to be used and the time available. If vehicular search is to be used, it may be possible to increase the size of the search area; however, any decision to do so must take into account the ground conditions (vegetation cover, etc.) and the abilities of the search team. The origin and orientation of the search area is not as important but is probably best if it is defined as elements of a polar coordinate system, the origin of which will be at the center point of the PES. An example of this type of search area is shown in Figure 3. Here debris will be collected in 5° wide sectors in the central zone.

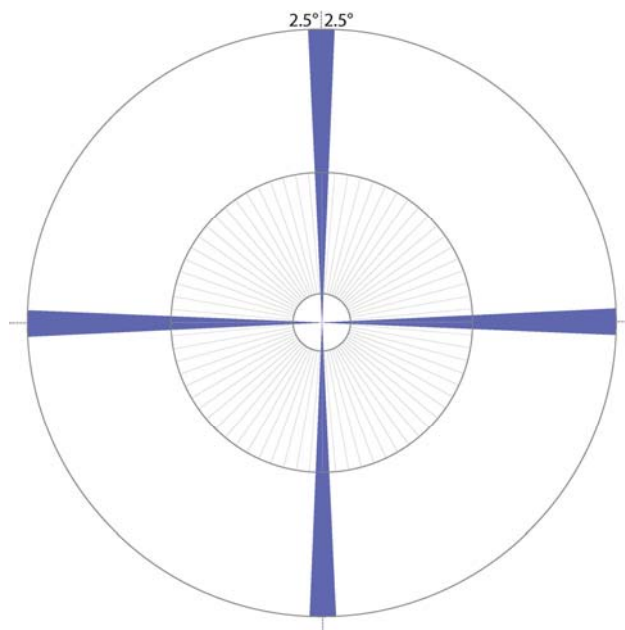


FIGURE 3. SYMMETRIC COLLECTION AREA (EXAMPLE)

3.7 Documentation

3.7.1 Search Management Process

This documentation extends from the test manager's search control techniques to the labeling of individual debris (either singly or collectively, dependent on the technique used). It is crucial that the search be carried out methodically with a high confidence in its completeness and consistency. The debris collectors need to be briefed at the start of the collection phase (and

possibly at regular intervals during the process) on the debris collection technique being employed and also on the importance of accuracy/fidelity during the collection process. This helps to maintain confidence in the completeness of the data.

A test diary/log should be maintained. This will provide chronological notes of all actions, observations, and decisions made on the test site and again forms an essential part of the test record.

3.7.2 Sample Data Sheets

When data are to be entered directly into spreadsheets, then the spreadsheet format and data categorization (e.g., debris type identifiers) must be agreed upon. Generic, site specific, and/or more detailed specific descriptors are appropriate and can be used. However, these must be well defined and each should be a sub-set of the more generic descriptors.

It may be useful to design and create event-specific data sheets to document test results. Prior to the test, all data sheets for use in post-test recording should be designed and agreed upon. Examples of data sheets that can or have been used for manual recording of debris data are shown in Figures 4 through 8. In Figure 4, the multiple data sets within each zone can be used to represent subsets of the total zonal information. Figures 4, 5, and 6 present samples of data sheets that have been previously used for collection of zonal data (NB: The mass bins shown in Figure 6 are defined in Table 1 and described in *Section 3.10 (Debris Mass)*). Figure 8 is a sheet designed for the collection of individual location information (NB: The letters shown in the background of the cells in Figures 7 and 8 represent the allowable entries for that cell).

ZONE _____		ZONE _____	
WEIGHT _____	WEIGHT _____	WEIGHT _____	WEIGHT _____
TARE _____	TARE _____	TARE _____	TARE _____
TOTAL _____	TOTAL _____	TOTAL _____	TOTAL _____
COUNT _____	COUNT _____	COUNT _____	COUNT _____
WEIGHT _____	WEIGHT _____	WEIGHT _____	WEIGHT _____
TARE _____	TARE _____	TARE _____	TARE _____
TOTAL _____	TOTAL _____	TOTAL _____	TOTAL _____
COUNT _____	COUNT _____	COUNT _____	COUNT _____
ZONE _____		ZONE _____	
WEIGHT _____	WEIGHT _____	WEIGHT _____	WEIGHT _____
TARE _____	TARE _____	TARE _____	TARE _____
TOTAL _____	TOTAL _____	TOTAL _____	TOTAL _____
COUNT _____	COUNT _____	COUNT _____	COUNT _____
WEIGHT _____	WEIGHT _____	WEIGHT _____	WEIGHT _____
TARE _____	TARE _____	TARE _____	TARE _____
TOTAL _____	TOTAL _____	TOTAL _____	TOTAL _____
COUNT _____	COUNT _____	COUNT _____	COUNT _____

FIGURE 4. SAMPLE DATA SHEET FOR ZONAL RECOVERY

Trial Number: _____
 Firing Number: _____
 Zone Number: _____

Sheet Number: _____

FRAGMENT TYPE	FRAGMENT MASS (kg)	DIM 1 (mm)	DIM 2 (mm)	DIM 3 (mm)	COMMENTS

FRAGMENT TYPES

B=brick
 C=concrete
 D=door
 E=energetic material
 F=miscellaneous steel
 M=miscellaneous other metals
 O=intact ordnance item
 P=case material from donor (primary fragment)
 R=rebar
 S=non-case material from donor

FIGURE 5. SAMPLE DATA SHEET: INDIVIDUAL FRAGMENT/DEBRIS INFORMATION WITHIN ZONE

Azimuthal Zone (deg)	Rmin (m)		Rmax (m)	Mass Bin	Concrete			Steel		
								Rebar		Other
					Roof	Floor	Wall	Roof	Wall	
-	-			1						
				2						
				3						
				4						
				5						
				6						
				7						
				8						
				9						
				10						
				G						

FIGURE 6. SAMPLE DATA SHEET: NUMBERS OF EACH TYPE OF DEBRIS WITHIN ZONE

3.7.4 Energetics and Instrumentation

All details of the test explosives, such as dimensions, masses, lot numbers, origins, history, stock numbers, etc. must be recorded. Details of camera and instrumentation locations, calibrations, fields of view, frame rates, etc. must be logged. If these are changed during the course of the testing, the changes must also be recorded.

3.8 Video/Cine and Related Instrumentation

A coordinated instrumentation plan must be produced and agreed upon before the event. The positions, as well as theoretical fields of view of all cameras and their associated calibration screens/poles will be needed in advance for survey purposes. However, it will be almost inevitable that local site conditions will dictate changes; prior to each test, all fields of view, as set up, must be agreed upon and documented.

3.8.1 Video vs. Cine

The choice of video or cine will be determined by the test director and the availability of assets. For explosive safety testing, there may be no real need for very high-speed recording. While it is accepted that cine usually offers the best resolution, state-of-the-art digital high speed or normal video offers adequate resolution with the advantage of immediate playback and is preferred by the authors, particularly on multiple-event tests. The ability to make changes to fields of view, exposure, etc. without the need to await film developing (which often cannot be done on or near remote test sites) adds greatly to the efficient management of the test.

3.8.2 Common Time Base

Experience has shown the importance of having a common time base across all instrumentation including cameras. A continuously running time base will be acceptable so long as Time Zero (the time of initiation of the charge) is recorded such that it may be superimposed on all other records.

3.8.3 Initial Velocity Determination

The measurement of the initial velocity distribution of structural debris is an area in which improvements and alternative means are sought. Thus far, data have been sparse and of relatively low reliability and accuracy. In addition to the optical recording of debris, attempts have been made to determine initial velocities of structural debris using various types of radar as well as flash X-ray. All of these have shown some promise, though there is still a significant

amount of technique development necessary. There is much room for innovative thinking in this area to improve the ability to measure this important parameter.

3.9 Post-Event Data Collection

Post-event data collection involves four processes:

1. Finding each debris piece
2. Determining the location, mass, and description of each piece
3. Cataloging of the information associated with each piece
4. Site remediation, including removal of all test-related debris pieces

An examination of the recovery area post-event will, generally, show that within some, to be defined, distance from ground zero, the number of debris pieces becomes so high that it is impractical to count or catalog individual bits. This region is known as the debris saturation zone. Within this area, major pieces should be cataloged and photographed and all debris pieces should be collected and their aggregate mass measured or estimated.

The collection methodology that is ultimately used will be selected on the basis of the pre-event planning process and an assessment of the on-site conditions present post-event. Under ideal conditions, the location, mass, and description of every debris piece would be noted and recorded. This may not always be practical. When it is not, two techniques with variations predominate. The first uses pre-determined (pre-event prepared) fixed recovery zones, as shown in Figures 1 and 2. The second involves recovering data in pre-selected areas, then determining their location, mass, and description. This selection process may be as simple as choosing all material ejected in preferred directions. It could also be as complete as selecting and cataloging all debris located beyond the edge of the debris saturation zone.

In all cases, however, the first step is the location of each debris piece. This process will usually involve a search by personnel who are either on foot or in vehicles. Because of the chance of missing or not locating items, vehicular search is only appropriate when debris may have been thrown more than, say, one kilometer. When this is thought to have occurred, it is better to use vehicles to transport personnel and equipment to the search area and then conduct the actual search on foot. The use of digital video footage could reduce time and errors spent searching far field areas for debris.

In addition to debris location, a thorough examination of the recovery area can produce other useful information. If a fragment has penetrated into other materials, an estimate can often be made of its impact velocity. Likewise, when debris impacts other objects or structures (trees, buildings, etc.) and leave marks indicating the point of impact, information such as trajectory directions can also be deduced. For example, if after an accident, a metal fragment is found

embedded in the trunk of a tree, the depth and angle of penetration can be related to its impact velocity and its position relative to the explosion site gives an indication of its direction of throw. Subsequent controlled experiments may, of course, be needed to quantify its speed.

3.9.1 Collection By Zone

In this approach, collection zones will have been defined and their boundaries located prior to the start of data collection (NB: *Section 3.6 (Site Survey)* describes the accuracy requirements). Each zone is searched by a recovery team. The number of personnel required for this operation will be determined by the size of the recovery zones and the amount of time allocated for the operation. Assuming favorable terrain conditions, one person can adequately search an area that extends approximately two meters to either side of his/her location; however, for effective, 100% pickup in high debris density zones, this may be reduced to as little as one meter. Often, more than one pass through a zone will be required in order to completely cover the area.

During the search, each debris piece located within the zone is identified, picked up, and transported either to a zone collection area (usually one corner of the zone) or to a central sorting area away from the grid. The number of pieces recovered within the zone and their description(s) (source and mass or mass bin) are noted and recorded. There are two options for determining the description. The first is to weigh everything in the field. This can be accomplished by either using a portable scale to weigh/record the descriptions of each piece or by sorting the collected material by source and then into mass bins and counting each pile. The second is to package the pieces from each zone with appropriate identification and then collect and remove all this material back to the central sorting area. At this location, each package is opened, and the same process is then used. It should be emphasized that all large debris should be photographed in situ with a scale reference in the field of view before they are moved or disturbed.

One variation on this method is the use of collection pans or debris traps. These are areas or structures of known dimension that are placed at selected locations around the test area. Because their dimensions are known, these provide point estimates of the debris density at that location. If enough of these traps are placed around the test area, then these point estimates can be used to estimate the total debris distribution. This method has the theoretical advantage that it appears inexpensive and easy to apply. In practice, however, this is usually not the case. In order to adequately sample the debris distribution, large numbers of collection boxes are required. Further, in some situations, the debris density is changing rapidly with range and/or azimuth; such changes may be missed or inadequately represented by a simple sampling technique. An additional problem with using this type of technique is that the pan or trap may interfere and modify the debris cloud and thus give incorrect information.

3.9.2 Individual Location

Once it has been decided that the location and description of each piece will be obtained, there are several options that can be used to achieve the location portion of this goal. These include, but are not limited to, compass and tape, the use of special binoculars that have a built in range finder and compass, conventional transit-based surveying techniques, Total Positioning Systems (TPS), Global Positioning Systems (GPS) or Differential GPS (DGPS) receivers, and systems which combine TPS with GPS.

A TPS is an optical instrument that combines an electronic theodolite (transit), an electronic distance measuring device (EDM) and software running on an external computer. The typical TPS EDM can measure distances with an accuracy of about 0.1 mm (0.00033 ft), but most surveying applications only take distance measurements to 1 mm or 0.0033 ft. Some TPS also have a GPS interface which combines these two technologies to make use of the advantages of both (GPS: line-of-sight not required between measuring points; TPS: high precision measurements), while reducing the consequences of each technology's disadvantages (GPS: poor accuracy in the vertical axis and lower accuracy without long occupation periods; TPS: requires line-of-sight observations and must be setup over a known point or within line of sight of two or more known points).

Each of these techniques has its strengths and weaknesses and each may not be appropriate for all situations.

If there is a relatively small amount of debris and this material is located close to ground zero, then a compass and tape approach could be appropriate. In its simplest form, the tape is used to measure the range of each piece from ground zero. The compass is used to estimate the bearing of each piece, also with respect to ground zero. While simple and easy to use in concept, this method has the highest potential for error—especially in the estimation of the bearing.

For those situations where there are too many pieces to use the compass and tape method and not enough to justify the use of a full, computerized survey, special binoculars might be used. There are at least two types of these specialized instruments:

- Those that have only a built-in range finder, and
- Those that have a built-in range finder and compass

If the first type is used, then multiple distances to structures or landmarks with known bearings and ranges from ground zero are recorded. These multiple readings can later be resolved into a range and bearing for each debris location. If the second type is available, they can be used to measure the range and bearing of each piece with respect to ground zero directly. A disadvantage with using binoculars is that the information usually must be recorded by hand or by direct transcription into a computer, though some models are equipped with a computer

interface. When the binoculars are linked directly with the computer, transcription errors will be reduced or eliminated. It should also be noted that the accuracy of laser binoculars is often limited to only ± 1 meter in range and $\pm 1^\circ$ in bearing.

Conventional survey techniques are always appropriate. Their main disadvantage is the amount of time required to complete each measurement. If there are large numbers of debris pieces involved, the amount of time required to conduct the survey may become prohibitive. This disadvantage is reduced if a computerized survey system with a laser range finder is utilized. With this system, a small crew (less than eight), and a moderate debris density, about one thousand points can be surveyed in an average day. However, in terms of total data retrieval, this efficiency will be reduced, as debris mass and description information are included against each item. With a computerized system, the information is automatically stored in computer memory, eliminating the potential error source that would be introduced by manual transcription.

All of these techniques work best where there is line of sight between the debris piece and ground zero. If there is no direct line of sight, intermediate survey points must be established—introducing the potential for additional errors.

Care should be taken when selecting any system for determining debris locations. This is especially true with many hand-held GPS systems. Their relative accuracy may be inadequate for the situation, thus precluding their use.

There exists another technique, which can be used as a backup to any of the methods discussed previously: aerial mapping/photogrammetry. As was demonstrated after the Distant Runner Test Series [21,22], conventional aerial photography and stereo photogrammetry techniques can be used to generate position information and size estimates for any debris piece with a size that is resolvable in the photograph. The use of such an independent method is doubly useful. First, it serves as a check on the results obtained by the other methods and, second, it can be used to identify/locate any debris that may have been missed on the initial survey. One limitation to this technique may be its inability to provide adequate debris identification.

Variations on this technique include infrared and ultraviolet imaging. The former is dependent upon temperature differences between the individual debris pieces and the surrounding terrain; these differences may be small and will decay rapidly. Ultraviolet imaging would require painting the PES with a material that would fluoresce in ultraviolet light, or embedding such a material within the PES structure. Care must be taken to ensure that such materials would survive the effects of the detonation.

3.9.3 Search Techniques

An orderly, repeatable procedure is strongly recommended for locating the debris. The exact method employed will depend on the circumstances, notably the:

- Debris density,
- Recovery area conditions,
- Number of people available to form one or more debris location crews,
- Experience/capability/motivation of such crews, and
- Time available to complete the effort.

3.9.3.1 Width Walk

A proven, deliberate method is to form a line of recovery personnel along the side of the sector and sweep across the sector from side to side. Although the personnel line up along the length of the sector, the search path is across the width of the sector. For this reason, this method is called a *width walk*. This method is depicted in Figure 9, and can be adjusted to fit the specific circumstances of any debris recovery effort (if there is sufficient time available).

The actual path followed by each searcher should be serpentine, as shown in Figure 9. The pace of the effort should be slow enough to ensure that few if any pieces are missed; the spacing of the personnel should be such that one searcher would be able to spot a piece missed by a searcher to either side. In addition to checking their neighbors, the search crews should be advised to periodically look behind themselves to check for pieces obscured by terrain, vegetation, or shadows. This technique is effective, but is labor intensive and time-consuming.

3.9.3.2 Length Walk

An alternate method, shown in Figure 10, is a *length walk* through each sector. Here, the recovery personnel line up across the width of the sector and sweep the length of the sector. This method may not be practical if there are not enough people to adequately cover the search area. This technique is also inherently less thorough. This is because the search area for which each individual is responsible increases as the search progresses along the length of the sector. At some point, the width of each person's search path may exceed the distance which can be searched with a high expectation of locating all of the debris (NB: *Section 3.9.1 (Collection By Zone)* describes this problem.)

It is also particularly difficult to achieve success if the walk is directly into or away from a bright, low sun. However, this technique is typically much faster, because there is less wasted movement between the current search area and the next area to be searched.

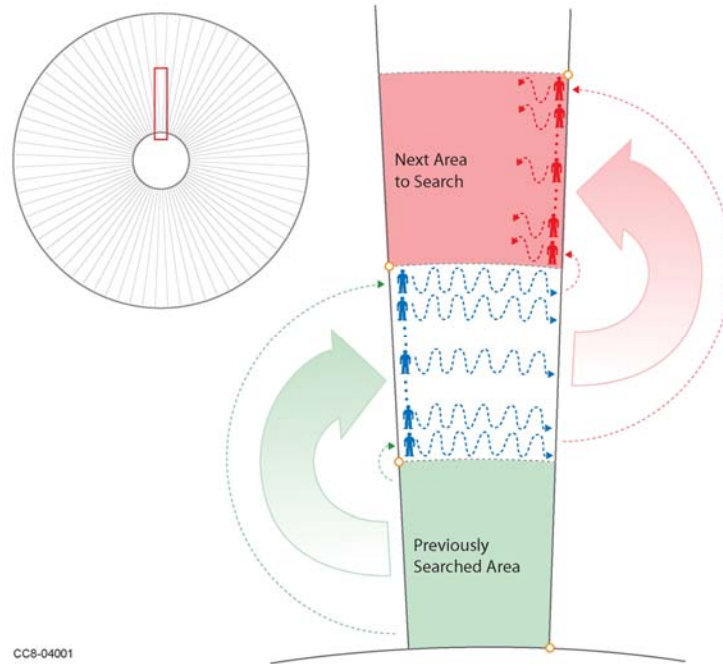


FIGURE 9. WIDTH WALK SEARCH TECHNIQUE

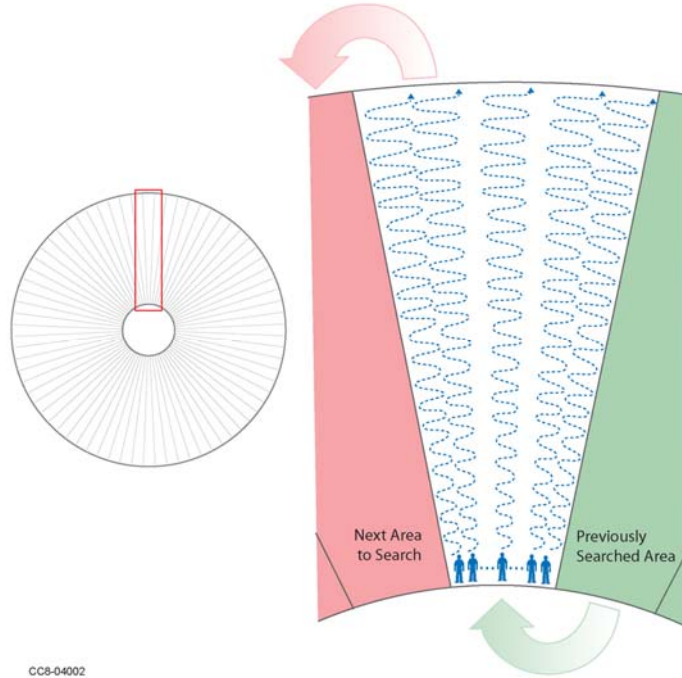


FIGURE 10. LENGTH WALK SEARCH TECHNIQUE

3.9.3.3 Error Checking

Whatever search technique is utilized, some sort of *error checking* or *miss rate* (number of pieces missed divided by the number of pieces collected) determination should be employed and the results documented and reported. In addition, if there are conditions such as sun height/angle or procedures that seem to contribute to an increased miss rate, then these should be documented and addressed immediately.

3.10 Debris Mass

As has been previously indicated, the mass of each debris piece is often required. In most situations, this will be determined by weighing the individual pieces. However, in those situations where the piece is too large to weigh easily, its maximum dimensions (length, width, and height) and its mass should be estimated. Other alternatives include:

- Weighing the debris piece later on a weight bridge (truck scales)
- Carefully breaking the debris piece into smaller components, weighing the components, and then summing the masses of the components

For all other pieces, the resolution of the scales that are used should be better than 1% of the total mass of the item. The minimum measurement increment that is normally required is a few grams. There are commercially available, portable, battery-operated scales with the required resolution, often with a computer interface.

When it is not practical or necessary to determine the exact mass of each piece, a binning technique can be used. Each piece of debris is categorized by a mass bin, rather than its actual mass. A recommended set of mass bins is shown in Table 1. An alternative approach that is applicable in most situations is the sorting of debris by dimension rather than mass. The size bands, also shown in Table 1, have been chosen to represent selected mass bands for steel and concrete. The size ranges shown for each mass bin were calculated by assuming that each debris piece was spherical in shape with a density of either concrete (2307 kg/m³ (144 (lbs/ft³) or steel (7849 kg/m³ (490 lbs/ft³)).

These mass bins provide a description (size, mass, and impact kinetic energy) for each mass bin for both steel and concrete debris. The impact kinetic energies were calculated by assuming that the material was falling at terminal velocity at the time of impact.

These bands are based on the mass bins that were originally defined for the United States risk-based explosives safety siting program, SAFER [23]. Since their definition, they have been used on at least two trial programs to characterize the debris that was collected [24, 25].

TABLE 1. MASS BIN CHARACTERISTICS

Bin Number	CONCRETE			STEEL		
	Mass (kg)	Size (mm)	Energy (J)	Mass (kg)	Size (mm)	Energy (J)
1	>24.5	>274	>136,920	>11.8	>140	>140,093
2	9.75 - 24.5	201 - 274	40,081 - 136,920	4.54 - 11.8	104 - 140	39,160 - 140,093
3	4.31 - 9.75	152 - 201	6,703 - 40,081	2.04 - 4.54	79 - 104	13,497 - 39,160
4	1.81 - 4.31	114 - 152	4,252 - 6,703	0.82 - 2.04	58 - 79	3,975 - 13,497
5	0.77 - 1.81	86 - 114	1,359 - 4,252	0.36 - 0.82	46 - 58	1,348 - 3,975
6	0.27 - 0.77	64 - 86	339 - 1,359	0.14 - 0.36	33 - 46	365 - 1,348
7	0.14 - 0.27	48 - 64	134 - 339	0.06 - 0.14	25 - 33	132 - 365
8	0.054 - 0.136	36 - 48	39 - 134	0.027 - 0.064	18 - 25	42 - 132
9	0.023 - 0.054	25 - 36	12 - 39	0.011 - 0.027	14 - 18	13 - 42
10	0.011 - 0.023	13 - 25	5 - 12	0.006 - 0.011	7.1 - 14	6 - 13
G	<0.011	<13	<5	<0.006	<7.1	<6

3.11 Probability of Fatality

It is frequently a requirement to relate the impact kinetic energy of a piece of debris to its probability of fatality, given that the debris hits the target. Figure 11 presents a curve of kinetic energy versus probability of fatality. This curve is based on the *Average Body Position* data described in Reference 26. The curve is a cumulative lognormal distribution fit to the data shown in Table 2.

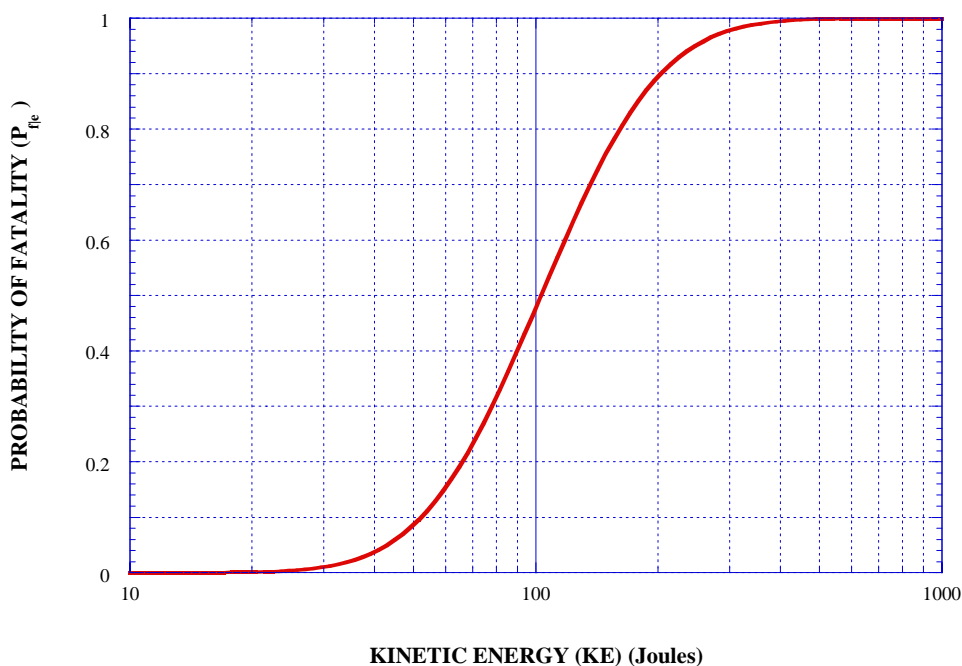
**FIGURE 11. KINETIC ENERGY VERSUS PROBABILITY OF FATALITY**

TABLE 2. IMPACT KINETIC ENERGY DATA

Probability of Fataality Given an Explosive Event And Exposure (P_{fe})	Kinetic Energy (KE) (Joules)
0.1	51.5
0.5	103.0
0.9	203.4

The direct formula for the cumulative lognormal distribution function does not exist in a closed form; however, Microsoft Excel does provide a function for its computation (LOGNORMDIST (X, Mean, Sigma)).

Based on Figure 11, it can be seen that a fragment with an impact kinetic energy of 79 Joules only has a 31% probability of being lethal. In order to achieve a lethality probability of 50%, an impact kinetic energy of 103 Joules would be required.

4.0 ACCIDENTS

The collection and analysis of the debris produced by accidental explosions generally proceeds in a similar manner to that described above for planned events. However, because it is an unplanned event, none of the pre-event planning can be performed. Generally, for accident situations, the location, mass, and description of each debris piece should be noted and recorded. The investigator should be aware that the accident scene might already include secondary debris that has nothing to do with the accident. An assessment of the site needs to be done to ensure that the debris is gathered with respect to the overall objective of the accident investigation.

In many situations there can be both operational and physical constraints that limit the scope of the debris collection effort. Debris collection may be restricted or, in some cases, prohibited because of the terrain or topography of the area around the accident site. Data recovery efforts must be coordinated with all other investigating activities. If the accident site is considered an *active crime scene*, i.e., if the cause of the accident is considered as either vandalism, sabotage, terrorism or other criminal activity, then the debris collection effort may need to be postponed until the criminal investigation is complete. At some accident sites, the crater and debris that were generated by the explosion may be, unavoidably, disturbed or compromised by the first responders entering the area. Such occurrences should be noted and documented in any post-event reporting. The debris collection area may be limited by local terrain or topography and the collection grid size and resolution may need to be adjusted and validated.

Care should be taken that any debris results that are obtained have not been altered or skewed by the response or investigation process, itself.

In addition, the generic descriptors used in test situations should be expanded to be more descriptive of each item. Because of the nature of the event, the interest in the results is often more than scientific. For this reason, every debris piece should be photographed if feasible. Included on each photograph should be a unique identification number that ties the photograph to an entry in a debris description catalog. Also, each photograph should contain an in-focus scale referent. Because of size, shape, or special features, some debris may require more than one photograph. Debris may have to be retained until the completion of all accident investigations and litigations.

The choice of an appropriate collection methodology will depend upon an on-site assessment of the situation. Because it is an accident and not a planned event, the terrain around ground zero will probably not be flat or level. There may be hills, valleys, vegetation, barricades or other

structures in locations that could influence the debris cloud. For this reason, a topographic map of the area that gives the locations of such items should be included with the debris catalog. The map should extend out to a range to include the farthest piece of debris. The contour scale of the map should be chosen such that all prominent terrain features in the vicinity can be resolved.

For many accident investigations, there may be insufficient funds available to perform as complete a debris collection effort as may be desired from a scientific or historic perspective. If this is the case, then the search parameters must be well defined prior to the start of the effort. The collection effort should extend outward to a range where the density of hazardous fragments (NB: A hazardous fragment is currently defined as one having an impact energy of 79 Joules (58 ft-lbs) or greater) falls below a value of 1 per 55.7 m² (1 per 600 ft²). Based on historical evidence, this distance can exceed a scaled range (actual range divided by the cube root of the NEQ) of 40 m/kg^{1/3} (101 ft/lb^{1/3}) (based on the known or estimated amount of energetic material involved in the event) for many types of donor structures [27]. The azimuthal search limits should be established after an on-site inspection of the area.

As previously noted, aerial photography and mapping may be useful in locating debris pieces and in being able to assess the symmetry of the debris field.

5.0 DEBRIS PICK-UP DATA ANALYSIS

5.1 General

The general aim of the analysis of the debris pickup data from tests or accident investigations is the generation of debris mass and number distributions and their defining functions. When considering accidents and tests, although the aim of the debris pickup data and analysis may be similar, the focus may be quite different. After an accident, the goal will likely be to help determine the size (e.g., 5 versus 50 kg), type (e.g., high order versus low order versus pressure rupture), and location (e.g., mix kettle versus fill hopper) of the event that occurred, with the goal of identifying where and how the accident happened. With a planned test, these are all initially known. According to the test or accident investigation circumstances, the degree to which this aim can be fulfilled will vary.

Care should be taken that situations do not arise that could mask or hide trends in the data. Two potential issues are:

- The sheer amount of debris may preclude more than a few sampled distributions
- The zonal dimensions used in a test may conceal some detail of the spatial distribution

An example of the first issue arose during tests in Australia [28] in which the debris distributions from explosions in small buildings were determined. Most of the debris was sorted to discard material that had no dimension greater than 50 mm (2 in) (deemed at the time to be equivalent to an object with a mass of 100 grams (0.22 lbs)). The remainder was simply counted. Only along two, orthogonal, 10° rays was a full mass analysis carried out. Mass distributions as a function of range were produced in those directions. To do more would have been prohibitively time-consuming.

The information gathered in any collection effort is generally a description of the piece, its mass, and its position or zone at or in which it was found, i.e., the point at which it came to rest. To arrive at that point, following its initial acceleration, it will have followed a ballistic trajectory defined by its velocity, mass and dimensions (which determine the drag) to its first point of impact. Upon impact, it may have buried itself, bounced, ricocheted or rolled. Dependent on which occurred, further ballistic, burial, bounce, ricochet and roll phases may have followed. At any point, this passage may have been perturbed by in-flight collision with other pieces of debris. Furthermore, at any impact point the piece of debris may break up and, thus, what is found at the pick-up point is only a part of something that was larger as it traveled over most of its journey.

As a result of all this, consideration of the debris data, in its *as-collected form* and in terms of measuring its potential damaging interaction with personnel or materiel targets must be considered as conservative (in terms of distance) for the following reason: Over the final stages of its passage from the explosion site to pick-up point, any piece of debris will be lower in energy and thus not as harmful as its initial impact with the ground

For many years this conservatism was accepted and all debris analysis was performed on the as-collected form of the data. In recent times, consciousness of the non-realistic treatment of the data coupled with a drive, for economic reasons, to control or minimize the degree of conservatism in consequence analyses has led to a re-examination of the methodology.

Looking simplistically at a storage or operating structure, most projected debris originates from three sources—the walls, the roof, and the floor. In general, each of these debris sources has a characteristic launch direction.

Roof and floor debris are mostly projected over a small angle about the normal to the ground; hence, they rise high into the air and return to earth at a high, nearly vertical, angle. As a result, they will only have a consequence at or near where they land.

Debris from the walls is, in general, projected over a small angle about the normal to the walls, nearly parallel to the ground. As it leaves the explosion site, it sweeps across the ground at a relatively low altitude and may, therefore, interact with any target (personnel or structures) as it passes. Thus, it is essential that the contribution to consequence of low-angle debris be integrated over its full path length. A method that attempts to accomplish this, called Pseudo-Trajectory Normal (PTN) Analysis, is described in a subsequent section.

As might be expected, in practice the picture is not so simple:

- Some debris pieces will be projected at intermediate launch angles and will only contribute to the consequences over parts of the passage to their final locations and
- Debris from roof, floor, and walls may not be separable and thus cannot be treated separately.

The requirement for a debris mass analysis is dependent upon the end use of the data. For risk assessment and safety distance determinations, it may not be necessary. However, for model development, it may be essential.

Historically, whether or not a full debris mass analysis was carried out, debris with low mass was removed from the analysis. In general, this was done to expedite the process and reduce costs. A downside to this procedure is that once the data collection is completed with small pieces of debris not being collected, there is no way to recover this data. It is better to collect as much information as is practical from the beginning, since there is no way of predicting what future analyses may require or desire.

5.2 Debris Inhabited Building Distance (IBD)

The debris IBD is the range at which the density of hazardous fragments falls below a value of 1 per 55.7 m² (1 per 600 ft²). Currently, a hazardous fragment is defined [4,17] as a fragment that has an impact kinetic energy of 79 Joules (58 ft-lbs) or greater. If the debris density versus range curve is or becomes non-monotonic and crosses the IBD density on multiple occasions, it is suggested that the crossing at the furthest (greatest) distance be used.

5.3 Incremental and Continuum Analysis

The positional debris information, whether collected in zones or as individual pieces, can be sorted and sub-divided into fixed polar zone populations of debris density, $N_{r\theta}$. The debris density for that zone is then given by one of two formulae:

$$D_{r\theta} = 360N_{r\theta}/[(\pi\Delta r \Delta\theta)(2r+\Delta r)] \quad (1)$$

$$D_{r\theta} = 180N_{r\theta}/(\pi r_c \Delta r \Delta\theta) \quad (2)$$

where

- $D_{r\theta}$ = zonal debris density ($N_{r\theta}$ /zone area)
- $N_{r\theta}$ = number of pieces in zone (r,θ)
- r_c = radial distance from ground zero to the center of the zone
- r = radial distance from ground zero to the inner boundary of zone
- θ = polar angle of the center of zone in degrees with respect to a coordinate system centered at ground zero
- Δr = incremental zone depth
- $\Delta\theta$ = angular width of zone in degrees

Fragment/debris density distributions as a function of range and polar angle can then be plotted. An example of such a plot is shown as Figure 12 [28].

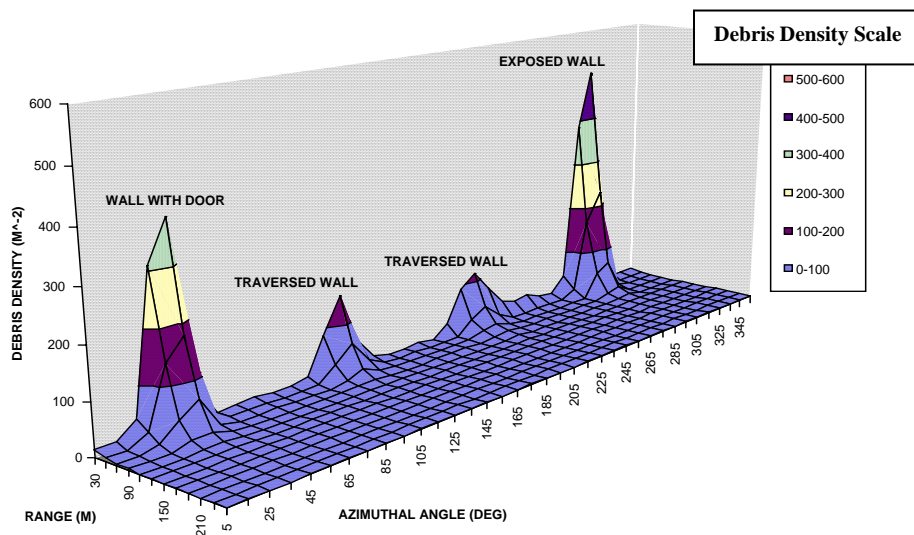


FIGURE 12. DEBRIS DENSITY VARIATION – EXAMPLE

Collection of individual debris locations/masses for each piece of debris can result in dauntingly large amounts of data. A recently completed trial [29] involving the collection of debris produced by a detonation inside an ISO container resulted in a data file with over 4500 entries. Table 3 shows a portion of that data file. (NB: The 4500 entries were the result of data collection over 185° of azimuth. If a full 360° collection had been accomplished, the data file could have had over 10,000 entries. A follow-on trial with a higher NEQ that did involve a full 360° recovery generated a data file with over 25,000 entries)

TABLE 3. SAMPLE DATA FILE

Day	Item Number	Angle (°)	Distance (m)	Mass (g)	Mass Bin	Source
1	1	358.97	100.90	220	6	I
1	2	358.97	100.86	100	7	I
1	3	358.56	101.81	33	8	T
1	4	358.49	101.47	66	7	I
1	5	357.60	104.16	21	9	I
1	6	358.87	106.59	9	10	I
1	7	359.45	106.46	91	7	T
1	8	359.94	106.78	7	10	I
1	9	1.14	107.38	18	9	T
1	10	2.00	104.54	9	10	I
1	11	2.59	105.50	22	9	T
1	12	2.64	105.79	12	9	U
1	13	2.40	107.00	130	7	T
1	14	2.89	108.33	60	8	U
1	15	1.87	110.05	25	9	T
1	16	2.43	113.04	16	9	I
1	17	1.68	112.65	51	8	I
1	18	1.35	112.70	19	9	T
1	19	0.40	111.53	1094	4	T
1	20	0.43	111.53	20	9	T

The type of data shown in Table 3 can be analyzed using the *Pivot Table* function contained in Microsoft Excel. A pivot table enables the creation of frequency distributions and cross-tabulations of several different data dimensions. In addition it allows the display of subtotals and any level of detail that is desired. A pivot table analysis was used on the full data set (from which Table 3 was extracted) to determine the number of debris as a function of sector (azimuth), range band, and mass bin. A portion of the results of this type of analysis is shown as Table 4.

TABLE 4. PIVOT TABLE ANALYSIS OF DEBRIS DATA (SAMPLE)

Sector	Range Band	Mass Bin										
		1	2	3	4	5	6	7	8	9	10	g
01 357.5° - 2.5°	A 100-125 meters				2	2	1	6	7	8	5	
	B 125-150 meters					1	3	3	10	13	5	
	C 150-175 meters						2	5	8	16	5	1
	D 175-200 meters					1	2	7	7	6	1	
	E 200-225 meters					1	1	5	2	5	3	
	F 225-250 meters			2			1	3	6	2	1	
	G 250-275 meters				1				2	2		
	H 275-300 meters			1		2						
	I 300-325 meters					1			1			
	J 325-350 meters					2						
	K 350-375 meters								1	1		
02 2.5° - 7.5°	A 100-125 meters		1			2	2	4	11	19	8	
	B 125-150 meters					1	4	6	19	15	14	5
	C 150-175 meters						1	2	6	14	12	6
	D 175-200 meters				1		3	3	8	17	9	3
	E 200-225 meters					1	2	3	11	8	4	
	F 225-250 meters						5	5	9	8	2	
	G 250-275 meters				1		1	1	4	3	2	1
	H 275-300 meters				1			2	3	1		
	I 300-325 meters					2			1			
	J 325-350 meters							1	1			
	K 350-375 meters								1	1		
	M 400-425 meters						1			1		
	N 425-450 meters							1		1		

In 1994, as a method of improving the statistics associated with the debris analysis procedures and to correct problems that had been exposed in the fixed grid methodology, Jacobs and Jenu [30] proposed a new methodology for analyzing these debris distributions. Their algorithm utilized a moving grid, using a procedure similar to that for calculating a sliding average. In this procedure, the analyst examines the radius-azimuth data and selects realistic bounds (minimum and maximum angles and distances) for analysis. Once a starting point is selected, a value for a sector of an annulus to be used as the “electronic debris collection pad” is also chosen. The methodology calculates the area of this pad, counts the number of fragments on that pad and then calculates the fragment density at that point using Equations (1) or (2). It then creates another sector of an annulus of the same angular width, some increment further away from ground zero and calculates the debris density for that sector. It continues in this manner until the leading

edge of the sector of the annulus includes the last fragment to be considered. As before, the coordinates of the sector are those of the center point of the annulus.

5.4 Pseudo Trajectory Normal (PTN) Density

In 1990, the Secretariat of the DDESB recommended that all debris densities should be measured as *trajectory-normal*, i.e., a density measured in a plane perpendicular to the trajectory at any point. This is difficult, if not impossible, to determine experimentally. Ground surface collection data, on the other hand, are straightforward to obtain. In order to approximate *trajectory-normal* densities, it was proposed that a *pseudo-trajectory-normal* (PTN) density be defined. At a given location, this density would be computed by defining the number of debris pieces to be considered as all hazardous debris material at that location plus all hazardous material that had to pass through that location to reach a greater range. One of the following two formulae can be used to compute these densities:

$$PTN_{r\theta}(i) = [360 / (\pi \Delta r \Delta \theta \{2r + \Delta r\})] \sum_i^{i \max} N_{r\theta}(i) \quad (3)$$

$$PTN_{r\theta}(i) = [180 / (\pi r_c \Delta \theta \Delta r)] \sum_i^{i \max} N_{r\theta}(i) \quad (4)$$

where $PTN_{r\theta}(i)$ is the pseudo-trajectory-normal (PTN) zonal debris density for the i -th zone, r , r_c , and θ are as previously defined and $i \max$ is the number of the zone that contains the furthest hazardous fragment. A more detailed discussion of trajectory-normal and pseudo-trajectory-normal distributions and their computation is presented in Reference 31.

5.5 Composite or Modified Pseudo-Trajectory-Normal (MPTN) Density

As discussed previously, the process of computing pseudo-trajectory normal densities may be quite conservative, since many pieces are thrown well above the surface of a zone and, hence, would not interact with persons or structures in that zone. In order to make more realistic estimate of the true trajectory normal density, the DDESB Secretariat tasked one of the authors to re-examine the PTN algorithm and recommend updates or modifications. The results of this study may be summarized as follows. Instead of considering all debris passing through a zone as contributing to the density in that zone, estimations indicate that only 1/3 of such debris contributes. It should be noted that this nominal value of 1/3 adequately represents nearly all of the scenarios considered. Therefore, a Modified Pseudo-Trajectory-Normal (MPTN) density could be defined and used. This is defined for a particular location by considering all appropriate debris material at that location plus all 1/3 of all material that had to pass through that point to reach a greater range. The factor of 1/3 is an average value that accounts for the

different trajectory paths—high angle versus low angle. The appropriate modifications to Equations (3) and (4) are shown below as Equations (5) and (6):

$$MPTN_{r\theta}(i) = [360 / (\pi \Delta r \Delta \theta \{2r + \Delta r\})] [N_{r\theta}(i) + (1/3) \sum_i^{imax-1} N_{r\theta}(i+1)] \quad (5)$$

$$MPTN_{r\theta}(i) = [180 / (\pi r_c \Delta \theta \Delta r)] [N_{r\theta}(i) + (1/3) \sum_i^{imax-1} N_{r\theta}(i+1)] \quad (6)$$

The “1/3” factor used in Equations (5) and 6 was corroborated by the following exercise. A series of trajectories for steel and concrete debris were calculated using the computer code TRAJ [13]. The following assumptions were made about the debris:

- Two debris types: concrete and steel
- Debris shape: *chunky* (cuboid)
- Concrete debris
 - Mass = 0.045 to 45.4 kg (0.1 to 100 lbs)
 - Speed = 30.5 to 609.6 m/s (100 to 2000 ft/s)
- Steel debris
 - Mass = 0.009 to 4.54 kg (0.02 to 10 lbs)
 - Speed = 60.7 to 2133.6 m/s (200 to 7000 ft/s)

NB: The calculations were originally performed in English units.

For each combination of debris type, debris mass, and launch velocity, the fraction of fragments/debris that reach that location via high angle and low angle trajectories was computed. The average fraction reaching that location via low angles for the concrete debris was 0.223 ± 0.146 . Based on this it was proposed that if a value of 1/3 were selected for the low angle fraction, it would provide an upper bound for nearly all of the scenarios analyzed and assessed.

This factor was substantiated by an independent assessment made by the Science Panel of the Risk Based Explosives Safety Criteria Team (RBESCT) [32]. In any case, if the debris data and analyses are adequately documented, then the data can be re-analyzed by new methods for purposes of comparison and further improvement of methods.

5.6 PTN/MPTN Discussion

Because its use has increased significantly since its introduction, the PTN/MPTN concept has been examined by several investigators [33-35]. Independent of each other, at least three investigators reached the same conclusion—that the methodology was potentially flawed. The absolute value of the IBD that is determined is dependent upon the zone size selected. As discussed in Reference 33, engineering judgment is often used to determine the sector length. The document further states that using a constant increment biases the fragment density as the radius increases. As the sector depth approaches zero, the density could approach infinity.

Another example of this potential problem is illustrated in the following example, taken from Reference 35. Consider three test scenarios for debris data collected between 90 and 250 meters (295 and 820 ft). Each describes a different manner to assess the same test data.

- Scenario 1
 - Sector depth = 20 meters (65.6 ft)
 - Sector width = 10°
 - Calculated Debris IBD = 231 meters (758 ft)
- Scenario 2
 - Sector depth = 20 meters (65.6 ft)
 - Sector width = 5°
 - Number of debris adjusted to account for collection area change
 - Calculated Debris IBD = 213 meters (699 ft)
- Scenario 3
 - Sector depth = 5 meters (16.4 ft)
 - Sector width = 10°
 - Number of debris adjusted to account for collection area change
 - Calculated Debris IBD = 246 meters (807 ft)

There is a significant variation in calculated IBD value with change in collection zone dimensional parameters. The magnitude of the variability may come down to the gradient of the debris density versus range curve when it crosses the density value of interest.

At least two approaches have been proposed to resolve this problem. The first by Parker [33] is to choose a sector length equal to the radial arc length. This gives the characteristic of having a nearly square analysis area approximating the area of a spherical segment. This is illustrated in Figure 13.

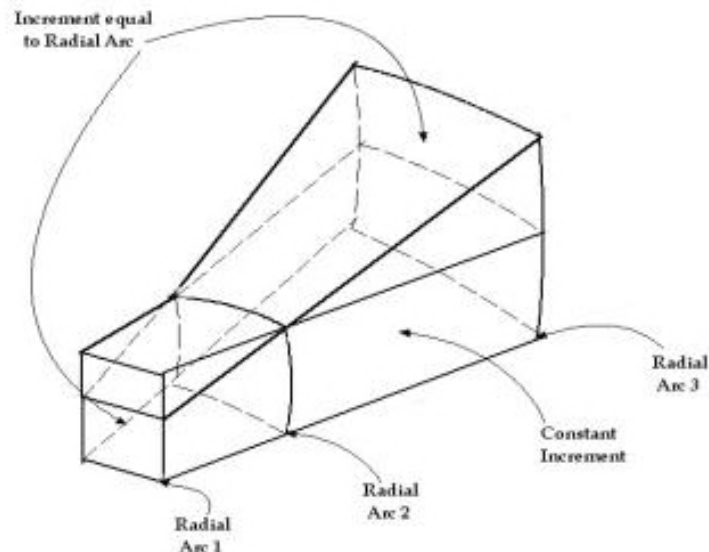


FIGURE 13. PTN DENSITY INCREMENT ILLUSTRATION

In the second approach, described by Gould [34], the trajectory of the debris is considered. A virtual vertical zone is placed at the center of each sector. Debris passing through the sector could impact this virtual surface or could pass above it. If it passes above it, it would not present a hazard to personnel or structures within the zone. This is shown in Figure 14.

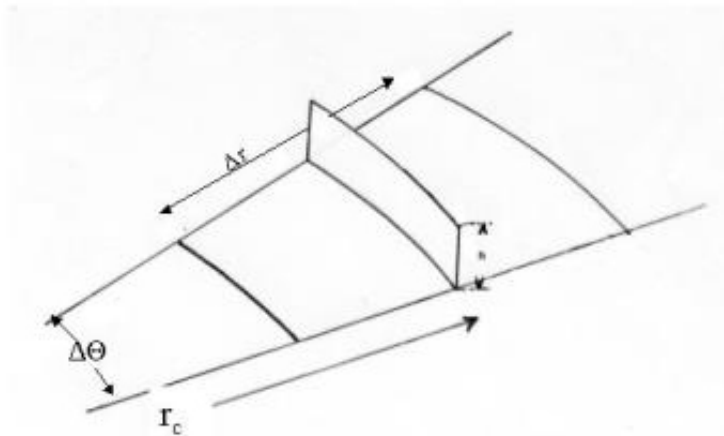


FIGURE 14. VERTICAL SECTOR ILLUSTRATION

The density of pieces within the zone is the sum of the density of material landing in the zone added to the density of material passing through the virtual wall. The height of the virtual wall is obviously important. It should be chosen to be representative of the types of targets of interest, i.e., personnel or structures. If the only interest is personnel, then a height of 2 meters (6.6 ft) is suggested; if structures are involved, then a height of 5 meters is recommended. For most analyses, a value of 5 meters (16.4 ft) ensures conservatism. When using this technique, it should be noted that if the debris is projected at a high angle, it could drop such that it passes through the virtual wall and still lands within the zone, which could lead to double-counting some of the high angle debris.

These concerns could call into question the use of the PTN/MPTN methodology for comparison of tests as different test agencies often use different zone dimensions. A solution to this dilemma might be for agencies to agree to use the same or similar zonal dimensions in their analyses—angular widths of 5°-10° and sector lengths of 20-30.5 meters (65.6-100 ft). Further consideration of these concerns is ongoing.

5.7 Debris Mass Analysis

If full debris mass data have been collected, they should be sorted, most certainly, by polar angle and/or by polar zone. If the angular increment has not been preselected, it should be chosen with regard to the rate at which the debris pattern changes with angle. If, for example, the mass

distribution in one lobe of a quatrefoil spatial distribution is required, then the polar angular increment should be chosen to encompass the whole lobe. If the mass distribution is to be examined as a function of angle then an incremental width should be chosen, which is sufficiently small so that it will not mask changes in distribution with angle.

It is recommended that the mass bands presented in Table 1 be used to characterize the debris that is collected. These bands are logarithmic in kinetic energy, which is most directly a function of the mass (because the velocity is dependent on the mass). This is of benefit if, for example, the goodness of fit to a Mott [36-38] or Porzel [39] relationship is to be examined.

A typical set of mass distributions [28] for different ranges is shown in Figure 15.

Either pre-test, post-test or at the data analysis stage, a decision may be made to limit the mass data collection or analysis. Very small debris will not be injurious, particularly at long ranges. However, its inclusion is often very useful in defining overall mass distributions.

Internationally, it has been the custom and practice to consider a debris kinetic energy of 79 Joules (58 ft-lbs) as the threshold for potential fatal effects. This criterion had its origins in Napoleonic times [40-42] but much more recently has been shown to adequately envelope the many more sophisticated debris mass/velocity/fatality models that have been developed [43]. However, as previously described, 79 Joules (58 ft-lbs) is not necessarily indicative of a 50% probability of lethality given impact.

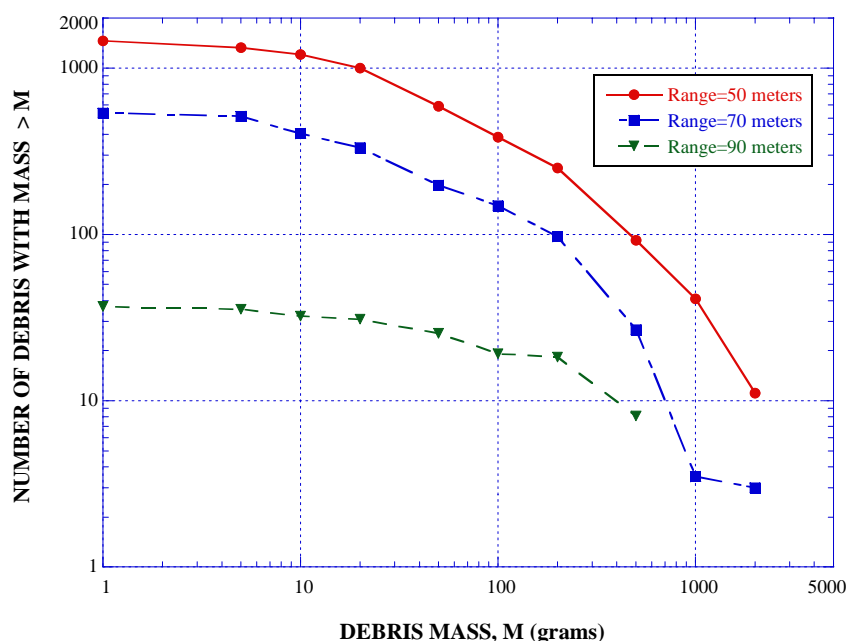


FIGURE 15. EXAMPLE DEBRIS MASS DISTRIBUTION

If it is assumed that the debris is falling at terminal velocity and that an impact kinetic energy of 79 Joules (58 ft-lbs) is required, it is possible to estimate the required mass (and size) of material necessary to achieve this energy. In making this estimate, the debris is assumed to be roughly spherical in shape and have a drag coefficient of 0.5 (NB: These assumptions are considered as representative of types of debris. If there is a priori knowledge of the debris material and shape, then the factors appropriate to this information should be used). With these assumptions,

- Steel debris (density = 7849 kg/m^3 (490 lbs/ft³))
 - Mass > 43 grams (0.095 lbs)
 - Diameter > 22 mm (0.87 in)
- Concrete debris (density = 2307 kg/m^3 (144 lbs/ft³))
 - Mass > 91 grams (0.20 lbs)
 - Diameter > 42 mm (1.65 in)
- Brick debris (density = 2054 kg/m^3 (128 lbs/ft³))
 - Mass > 98 grams (0.22 lbs)
 - Diameter > 45 mm (1.77 in)

It should be noted that this argument quite clearly excludes primary fragments from detonating ordnance. This is not considered to be a problem as, in most cases, the more massive debris from structures is thrown to greater distances than small detonation fragments and the greatest interest from the safety community's point of view is in far field effects.

It is not recommended that mass data distributions be restricted; i.e., all debris should be collected, cataloged, and analyzed. If this is not practical, and collection or analysis efforts must be restricted, then the following lower limits for debris mass are recommended:

- Steel debris: 40 grams (0.09 lbs)
- Concrete debris: 90 grams (0.20 lbs)
- Brick Debris: 95 grams (0.22 lbs)

5.8 Debris Initial Velocity Estimates

After the debris has been collected and its mass determined, questions are often raised about the initial velocities of the debris. For the planned event, these questions may be answered by the optical and/or electronic instrumentation. What about the unplanned event or the situation where an independent estimate of velocity is needed or required?

The procedure described in this section can be used to make a crude estimate of the launch velocity of debris that is projected into the far field. This estimate is based upon three pieces of information:

- (1) The final range of the debris piece,
- (2) The mass/size of the debris piece, and
- (3) The type of debris.

This procedure ignores ricochet and roll and assumes that they do not occur; i.e., the final impact point of each debris piece can be calculated by a purely ballistic trajectory (NB: The trajectories that are computed assume the debris is launched at its optimum launch angle—maximizing range for the given launch velocity). The method further assumes that individual debris pieces do not shed mass over the course of the trajectory or break up upon impact. It also assumes that the debris pieces can be represented as compact, *chunky* shapes, rather than long rods or spheres. Strictly speaking, this methodology applies only to far-field debris.

To date, the procedure has been established for steel and concrete debris. The velocity estimates that are produced are not unique or absolute. If a debris piece reaches its final location by ricochet or roll, then the velocity that is calculated will be higher than the true launch velocity (assuming an optimum launch angle). Further, if the debris piece reaches its final location via a launch angle that differs from the optimum, then the velocity that is estimated will also differ from the actual velocity.

The following equations, which were derived for an earlier version of this document, may be used to estimate the velocity:

$$\text{Velocity (m/s)} = A_m e^{(B_m * R)} \quad (7)$$

Equations (8) and (10) or (9) and (11) (depending on the type of material) are used to calculate A_m and B_m . With these coefficients and the range, Equation (7) may be used to estimate the velocity.

$$A_{m, \text{concrete}} = 5.41 + 1.79 * [\ln (M)] + 0.049 * [\ln (M)]^2 \quad (8)$$

$$A_{m, \text{steel}} = 7.54 + 1.27 * [\ln (M)] + 0.24 * [\ln (M)]^2 \quad (9)$$

$$B_{m, \text{concrete}} = 0.053 * M^{-0.304} \quad (10)$$

$$B_{m, \text{steel}} = 0.030 * M^{-0.326} \quad (11)$$

where

- M = mass of the debris piece in grams
R = range in meters from the center of the PES to the debris in question

As an example, consider a piece of concrete debris that weighs 454 grams that is found 300 meters from the center of a PES. Using Equations (8) and (10), values of 18.2 and 0.00825 are obtained for $A_{m, \text{concrete}}$ and $B_{m, \text{concrete}}$, respectively. Inserting these values into Equation 7 with a range of 300 m, a velocity estimate of 216 m/s is obtained.

For concrete debris, the equations are valid for masses between 45 grams (0.1 lbs) and 45,000 grams (99.2 lbs). For steel debris, they are valid for masses between 10 grams (0.022 lbs) and 4500 grams (9.92 lbs). The equations are valid for ranges between 50 and 1400 meters (164 to 4593 ft) for concrete and 100 to 2000 meters (328 to 6592 ft) for steel.

It should also be re-iterated that these equations provide approximations for the velocities and should only be applied to far-field debris.

6.0 SUMMARY

This document should be used by a wide variety of professionals. Of course, the program manager, test engineer, safety professional, and test support personnel lead the list. The list also includes the funding source and prediction modelers. Accident investigators should also be aware of the valuable debris data that can be obtained after an accident. The safety policy makers need to be aware of how the data they use to establish policy are gathered and evaluated.

By following the guidance provided in this document, it is hoped that data obtained through safety test and accident debris analysis will be able to be used to better predict the hazard from debris from an explosive test, accident or incident and, ultimately, improve explosive safety standards.

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